Field Enhancement at Grain Edges – Revisiting the "Knobloch-Model" in View of Our Effort to Understand "Hot Spots"

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Knobloch Model (1/17)

J. Knobloch, R. L. Geng, M. Liepe, and H. Padamsee

“High-Field Q Slope in Superconducting Cavities Due to Magnetic Field Enhancement at Grain Boundaries”

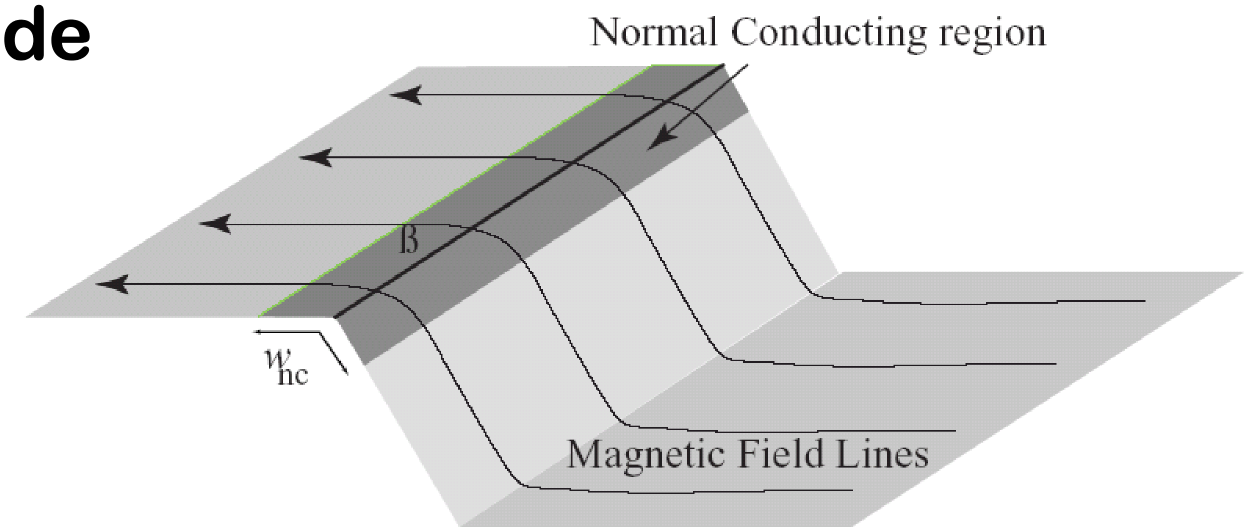
1999 SRF Workshop Santa Fe, USA

Knobloch Model (2/17)

- "effective" number of grains (from grain size and "effective" cavity area)
- (normalized) distribution of field enhancement factors (from surface topology studies)
- integrate FE factor distribution from B_{crit}/B to ∞ to compute the # of quenched grain boundaries at given B
- calculate power dissipation due to normal areas in quenched grain edges (assume "width" of quenched "band")
- Calculate power dissipation due to increased BCS loss in "adjacent" sc areas

Knobloch Model (3/17)

•only ½ of the edges of the grains have FE
•field enhancement only increases field component that is vertical to grain edge (and grain edges are randomly oriented to the field)
•quenched regions around grain edges are ~ 1μm wide



Knobloch Model Step by step (7/17)

Normalized (to 1) FE factor distribution:

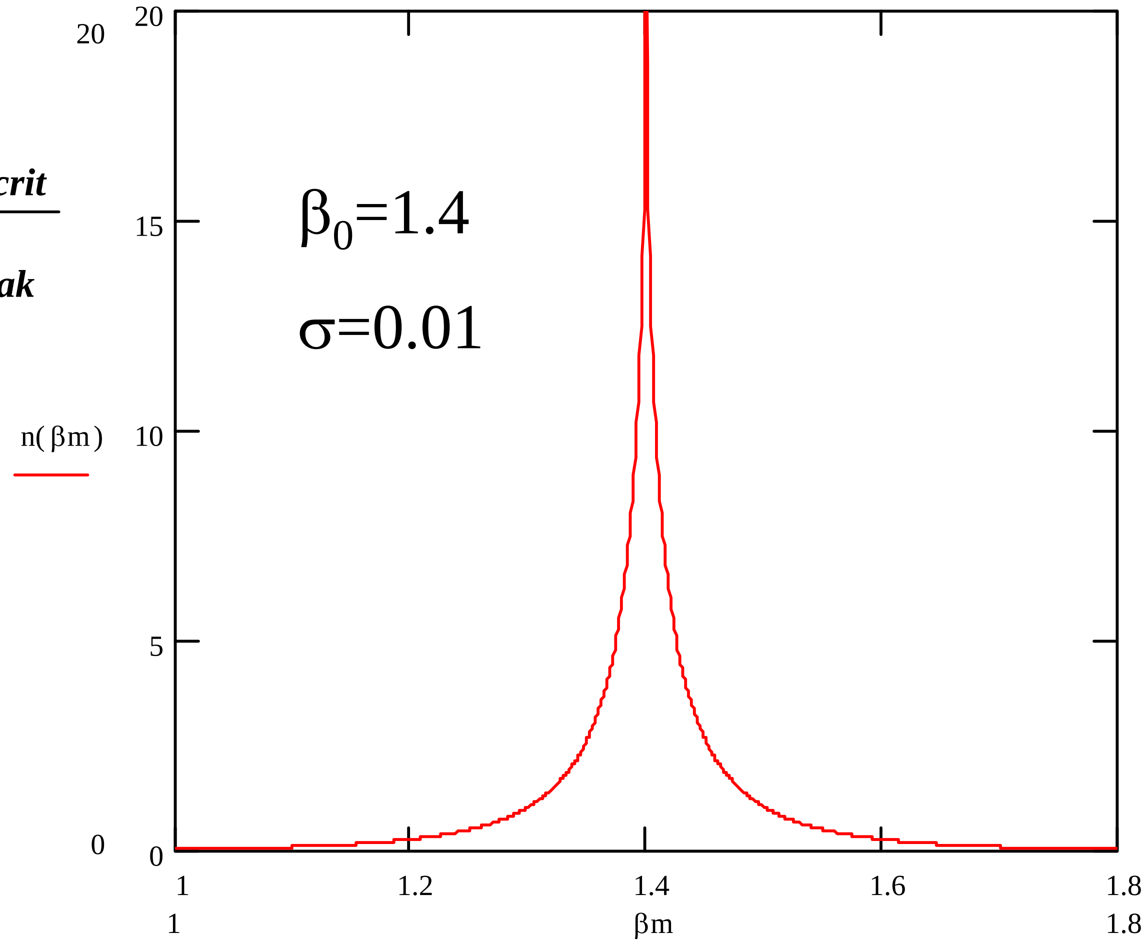
$$n(\beta) = \frac{1}{N} e^{-\sqrt{\frac{|\beta-\beta_0|}{\sigma}}}$$

$$\beta = \frac{B_{rf,crit}}{B_{peak}}$$

"guessed" distribution including some plausibility argument:

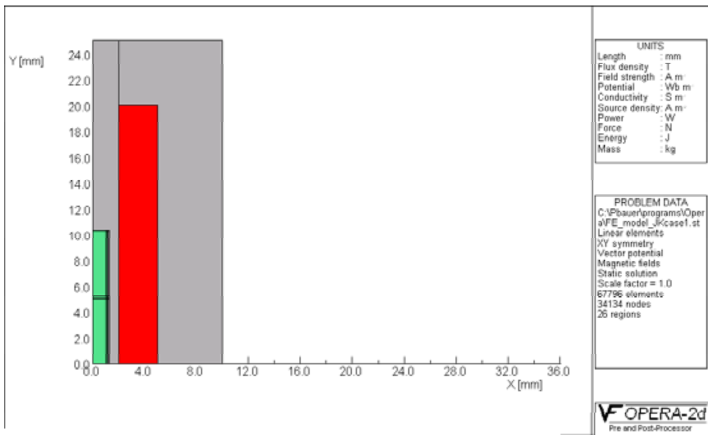
•max(β)<2.5 if no GB is quenched at 20 MV/m

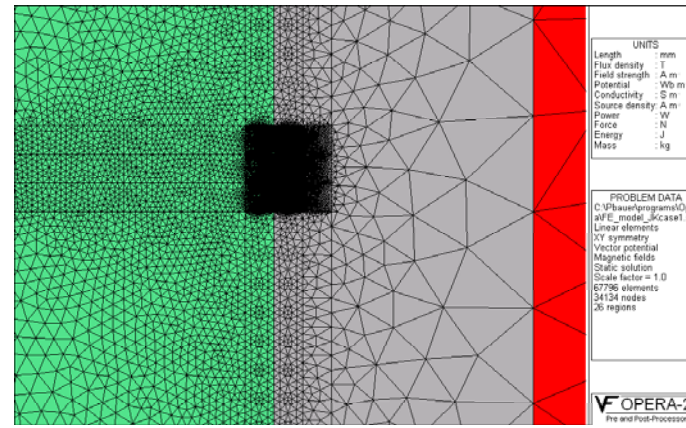
•Q-drop starts at ~35MV/
– β_0~5/3.5~1.4



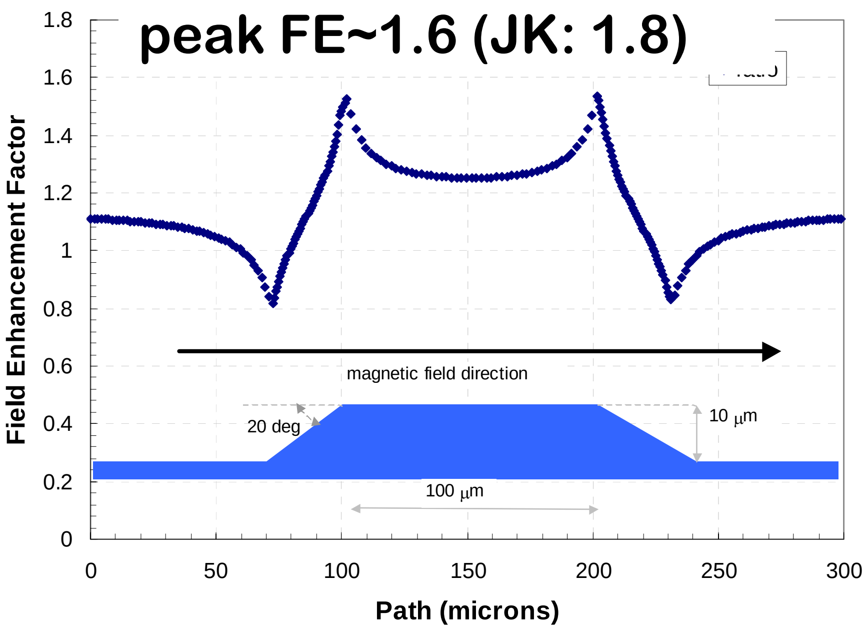
FE Model OF 10 MICRON "STEP"

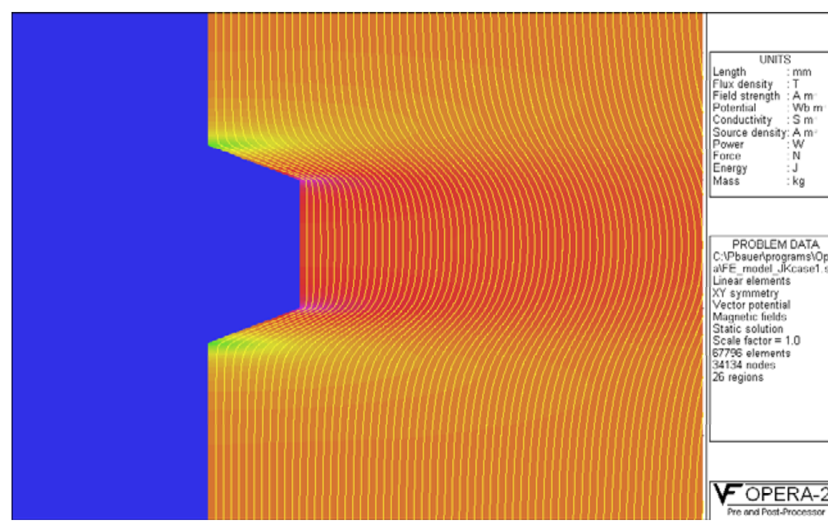
FE Model of 100 μ grain that sticks out by 10 μ





peak FE~1.6 (JK: 1.8)



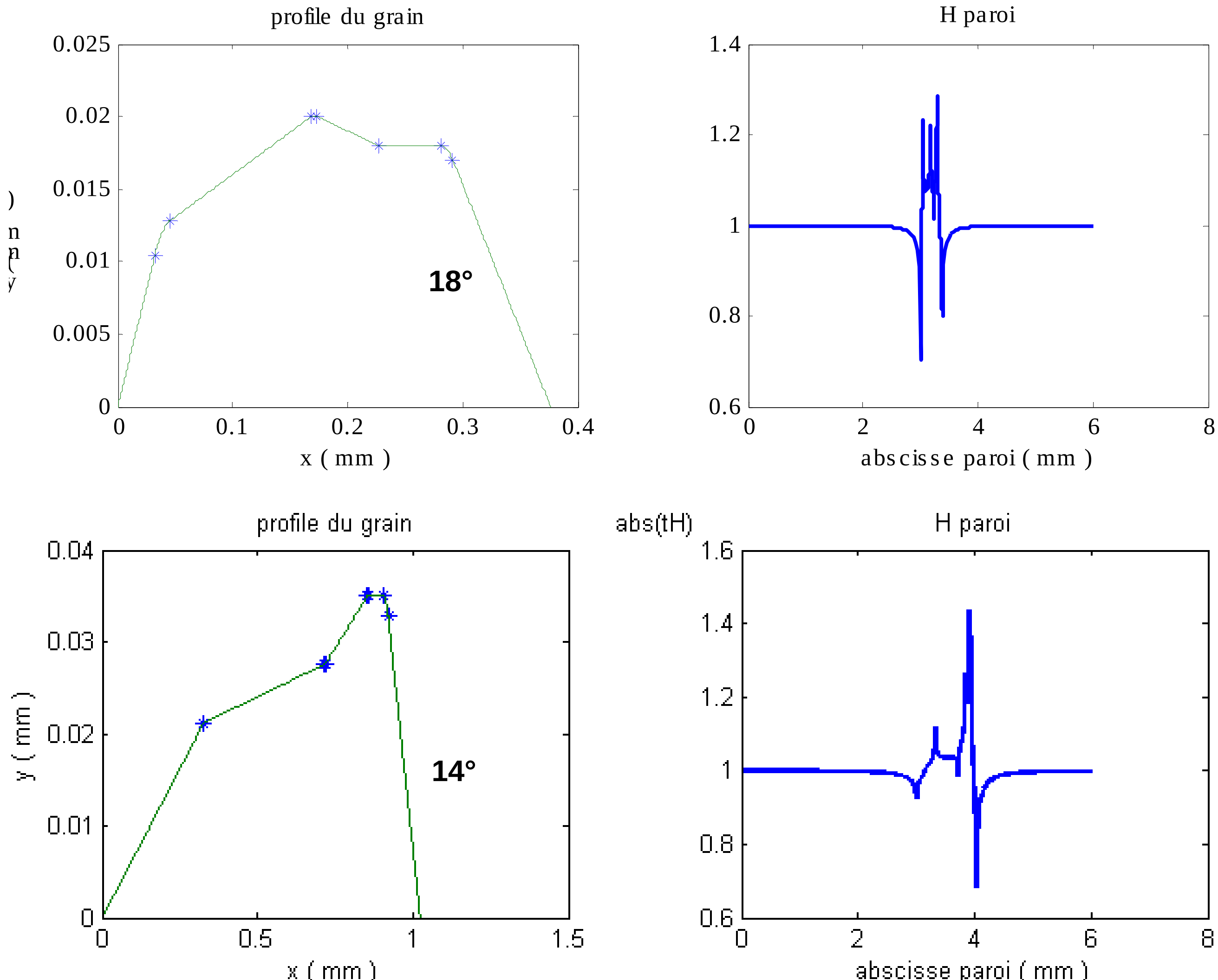


FE Models at CEA

FE Models of different grains profiled with “replica” technique;

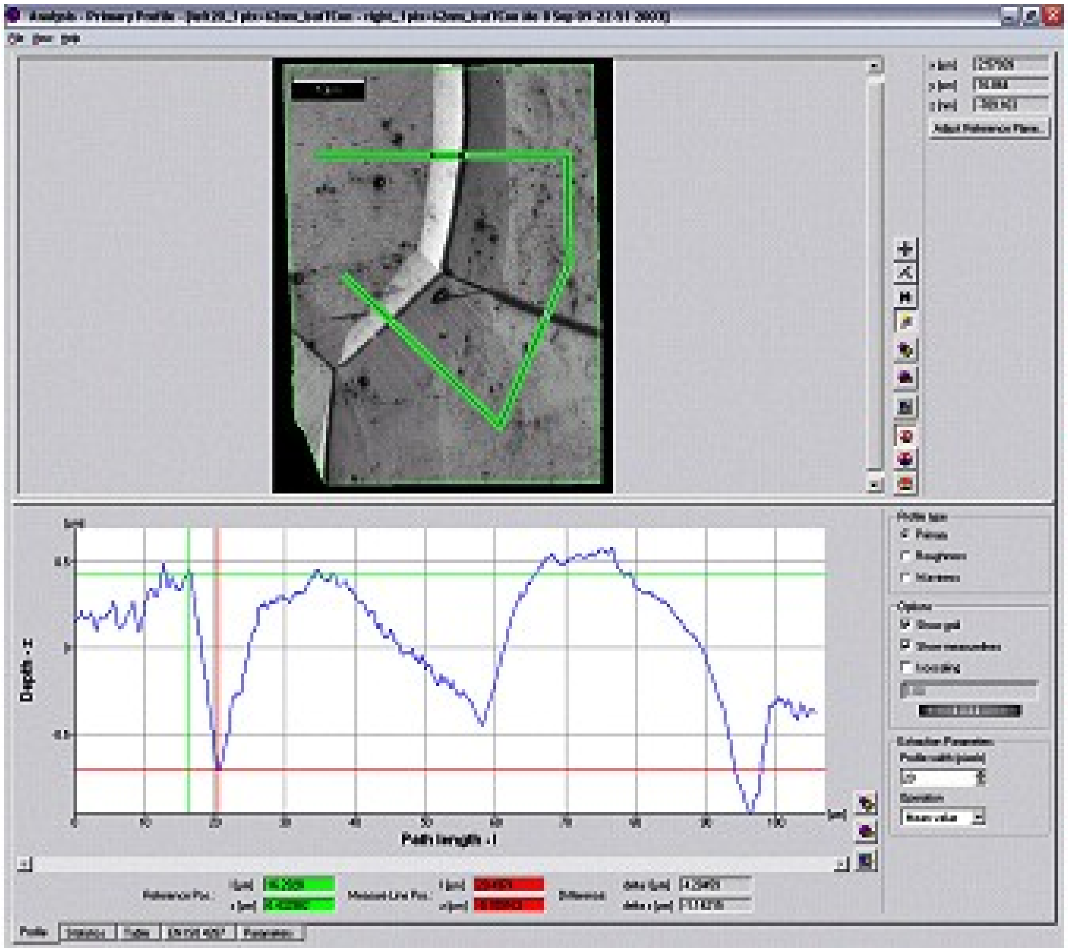
400μ grain that sticks out by 20μ - FE~1.3,

1 mm grain that sticks out by 35μ - FE~1.4



Michel Desmons / CEA

Real Surfaces



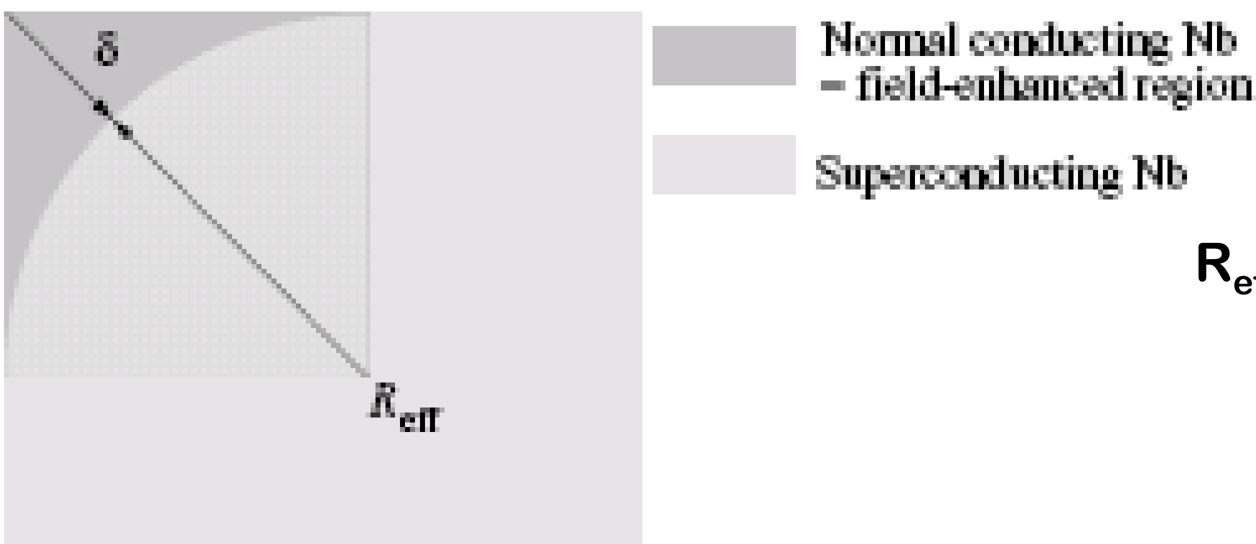
How appropriate is the distribution function?

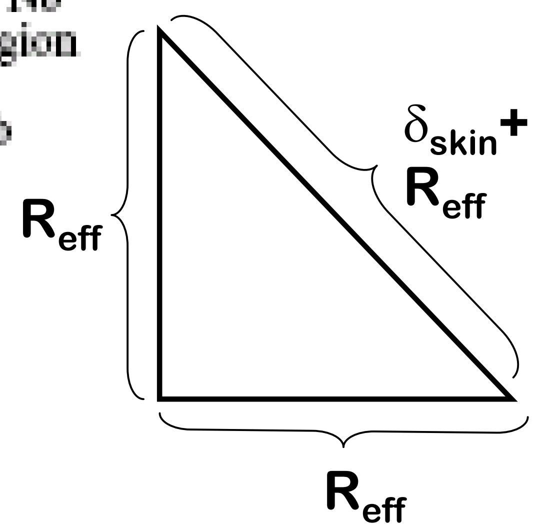
Knobloch Model Step by step (8 / 17)

Upper limit on field enhancement factor:

Skin effect limits the maximum edge angle:

$$R_{eff} = \frac{\delta_{skin}}{\sqrt{2}-1} = 2.4\,\delta_{skin}$$

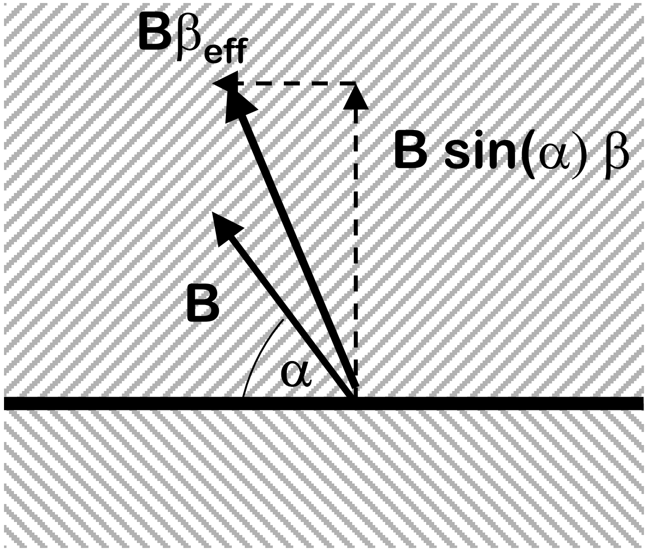




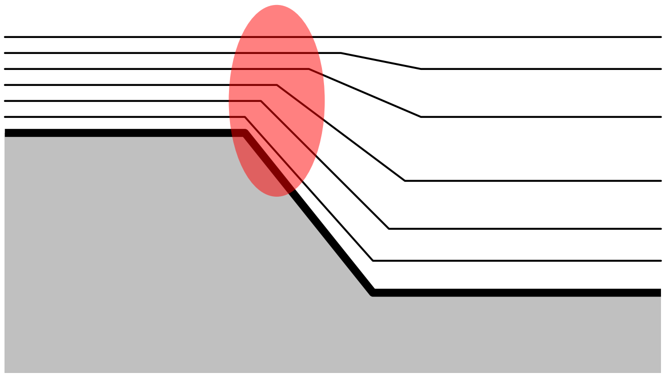
Knobloch Model Step by step (9 / 17)

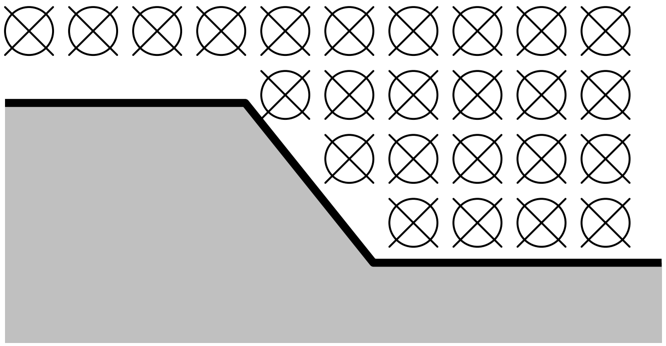
Calculation of effective β:

$$\beta_{eff} = \sqrt{\left(\beta \sin(\alpha)\right)^2 + \cos^2(\alpha)}$$



Field enhancement only affects the field component that is vertical to the grain edge:



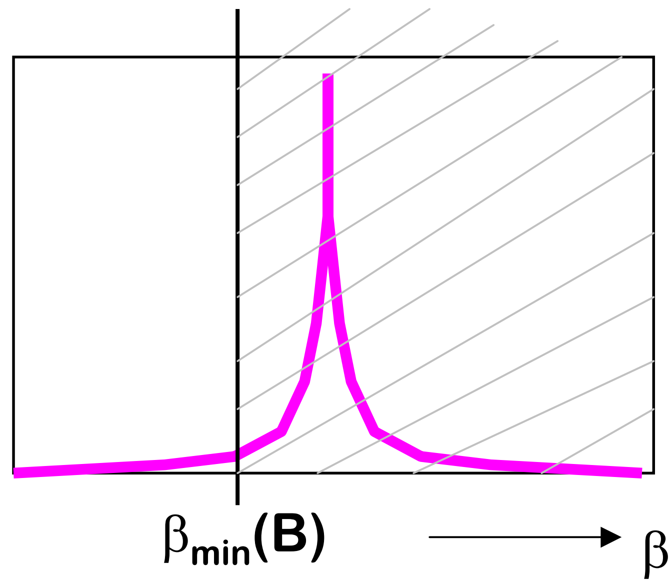


Knobloch Model Step by step (12/17)

Number of quenched grain edges:

$$N_{geq}(B) = \frac{2}{\pi} N_{ge} \int_{\beta_{\min}(B)}^{\beta_{\max}} \int_{\alpha_{\min}(B,\beta)}^{\pi/2} n(\beta)\, d\beta\, d\alpha$$

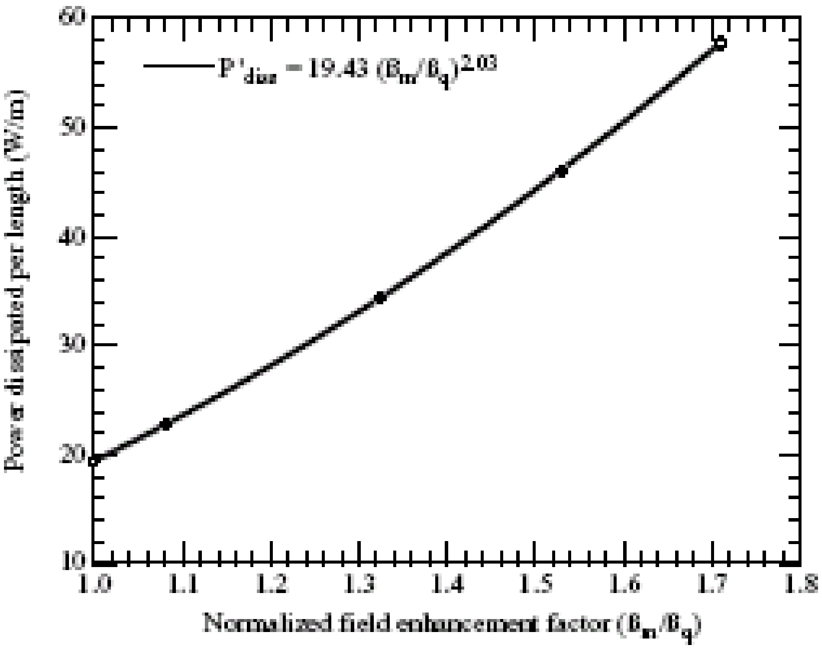
β_{min} is the FE factor at which, for a given field B, a particular grain edge reaches $B_{rf,crit}$ (I.e. quenches). β_{min} is infinity (or 10 here).



Knobloch Model Step by step (13/17)

Increased BCS loss in adjacent regions:

$$\frac{P_{diss}^{incl\ AR}}{P_{diss}^{excl\ AR}}(B)=\left(\frac{\beta_{eff}(\alpha,\beta)B}{B_{rf,crit}}\right)^{2.03}$$



Using a finite element model Jens computed the additional BCS loss in the region adjacent to a quenched grain boundary.

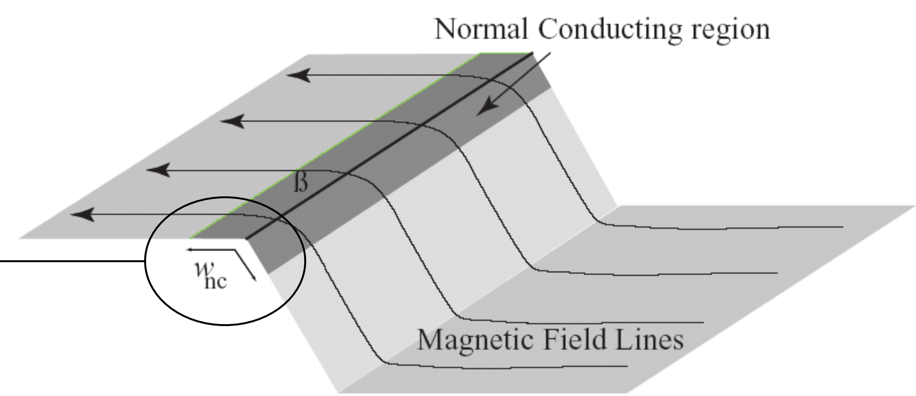
Since the above factor depends on β_{eff} it needs to be included in the b-integral!

Knobloch Model Step by step (14/17)

Width of quenched region w_{nc}:

Jens' FE model also gave indications as to the temperature stability of the adjacent region and the width of the quenched region. The region appeared stable and the width, w_{nc}, generally remained below 1 μm!

Here we always assume a width of 1 μm!

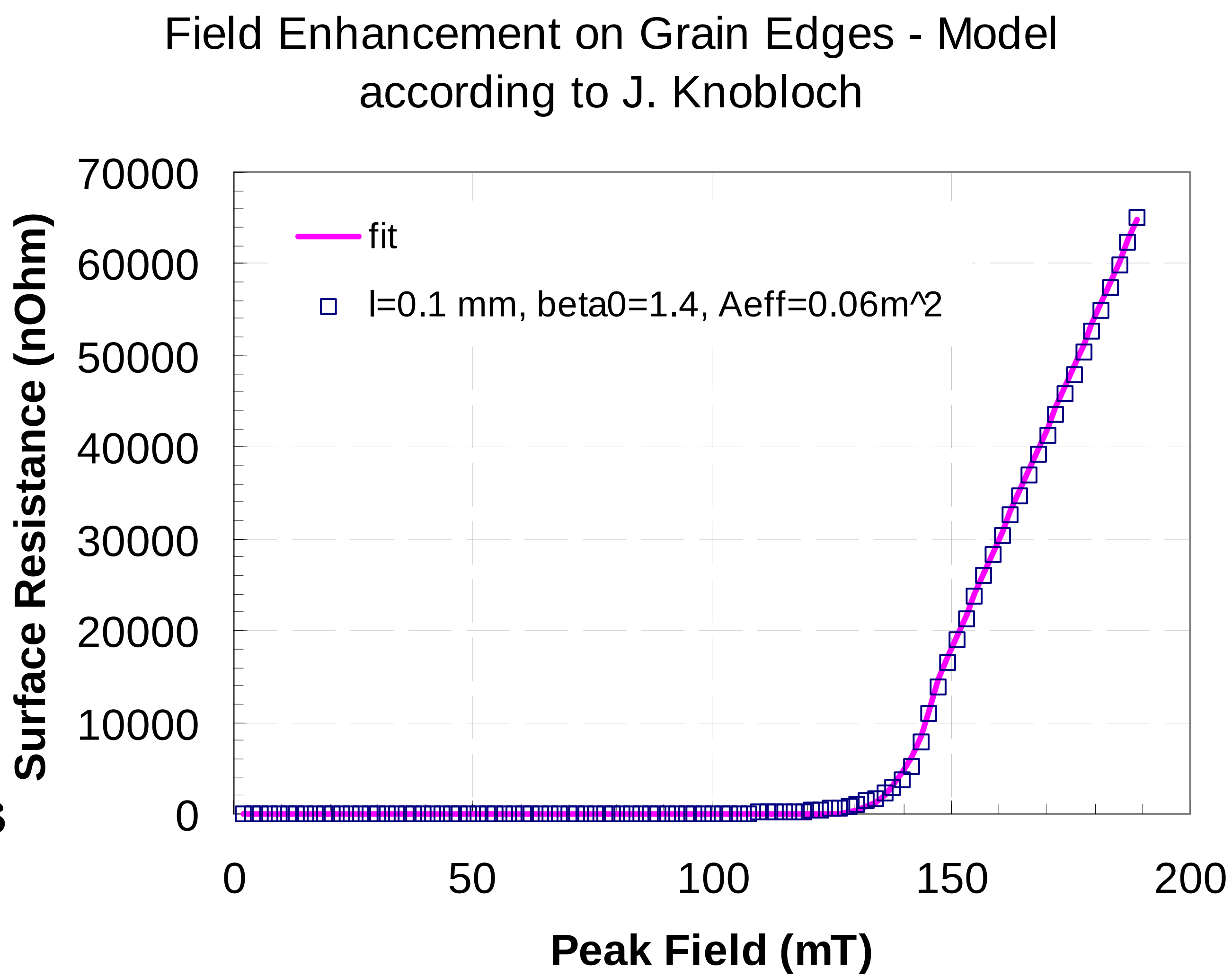


Knobloch Model Step by step (16/17)

Calculated Surface Resistance with β_0=1.4

$R_{s,norm}$~ 1.5 mΩ

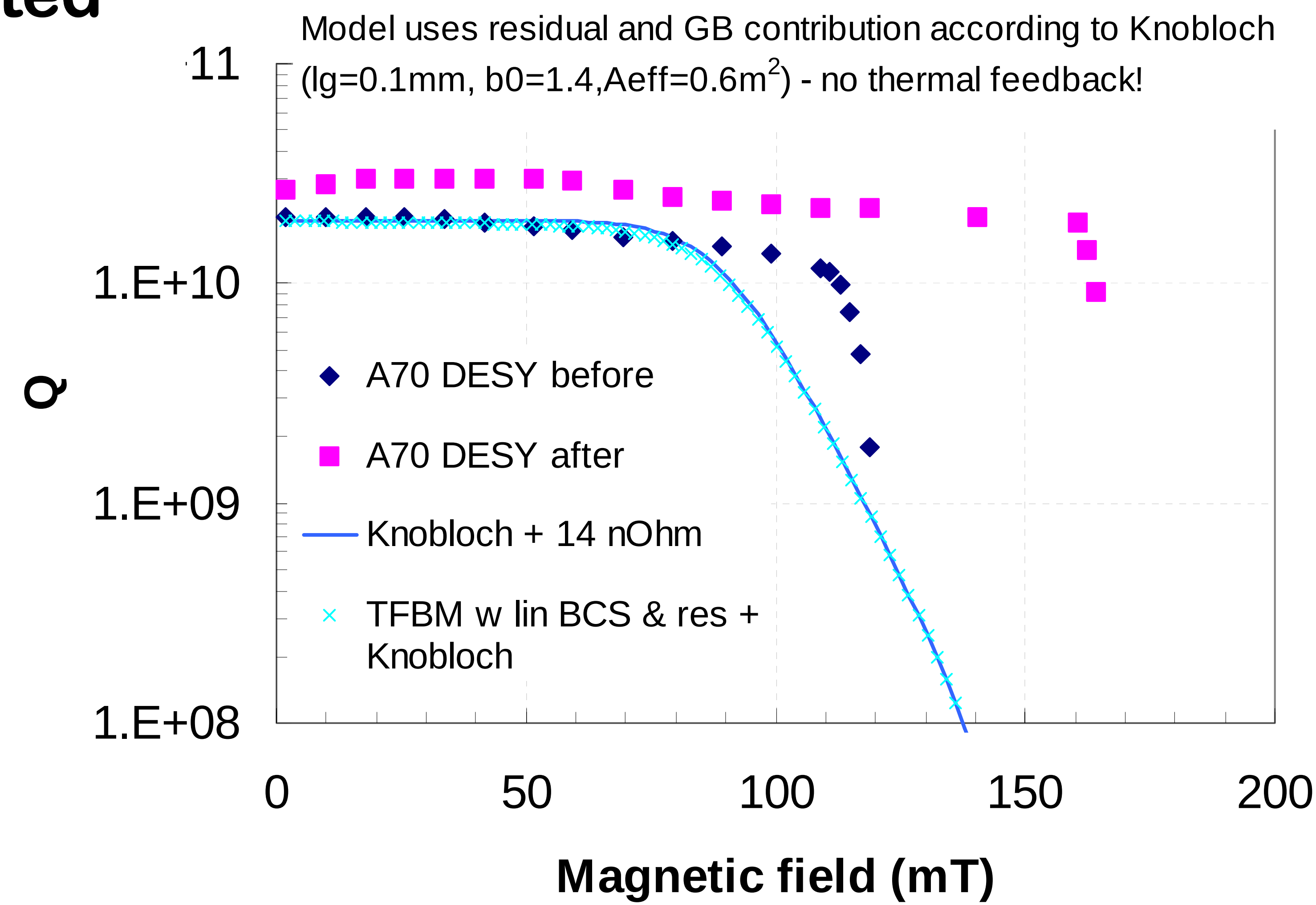
~6000 GB edges (= 0.6 mm^2 normal area) quenches at 25 MV/m



Knobloch Model Step by step (17 / 17)

Calculated Q with β_0=1.4 :

~70000 GB edges (7 mm² normal area) quenches at 35 MV/m !

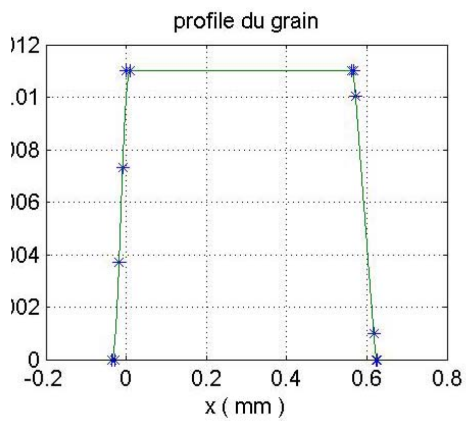


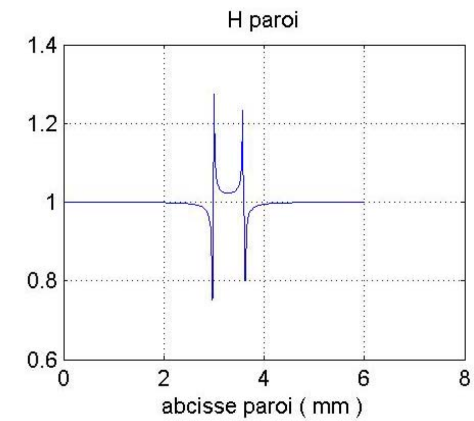
Issues in Knobloch Model

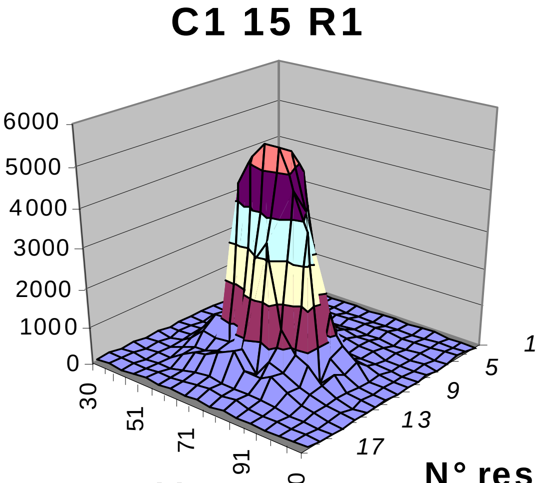
- Q-drop OK but onset below 25 MV/m with given distribution (β_0=1.4);
- Baking effect cannot be explained;
- Quench – see next slides

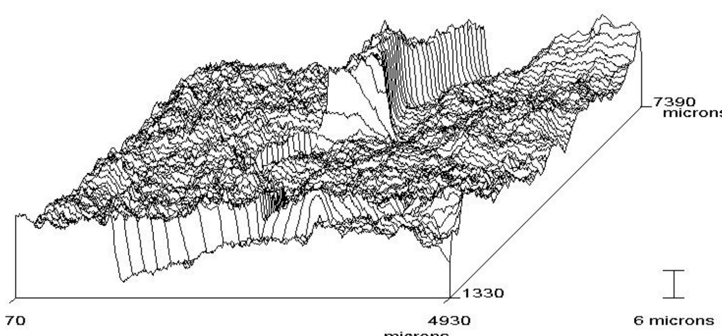
Cavity Quenching Due to FE

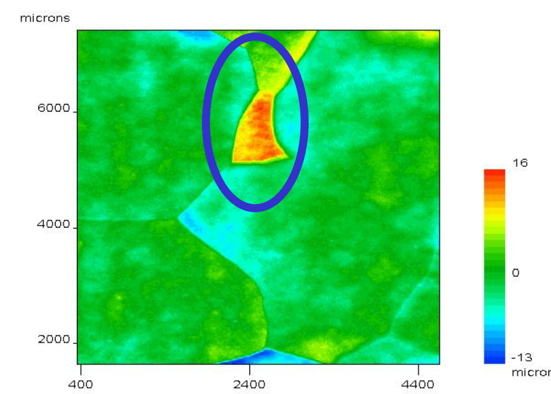
One particular grain is believed to have caused a quench in a CEA prototype cavity: thermal mapping shows ~5 K peak temperature before quenching. Modeled FE: ~1.3











Claire Antoine / CEA

Cavity Quenching Due to FE

2 x2 mm x 1μm + 2 x 0.5 mm x 1μm = 0.005 mm^2 = 100 times smaller than Knobloch model normal area at 25 MV/m (as discussed above)! The Knobloch-model does not predict this quench!

If it is true that a grain can cause a quench then the Knobloch model needs to be revisited also in terms of the thermal and electromagnetic processes taking place in the grain.

Is the thermally affected zone really only 1μm wide and thermally stable? What exactly is going on?

MINIMUM QUENCH ENERGY PROBLEM???

Possible improvements

- More realistic FE factor distribution;

- Better understanding of physics of quenched zone width (static and dynamic) – vortex penetration;

- Integration of Knobloch model into Gurevich's hot spot model (replace "$(\beta E)^2$ formalism");
- Introducing a mechanism that can explain the baking effect in the frame of this model;

Better FE Distribution

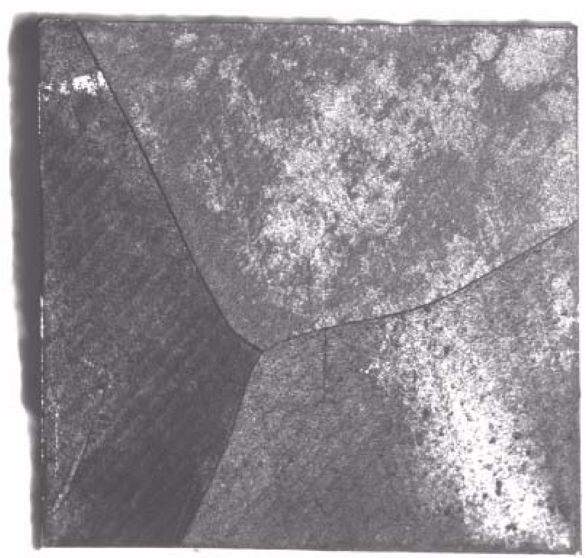
- Better FE factor distribution?

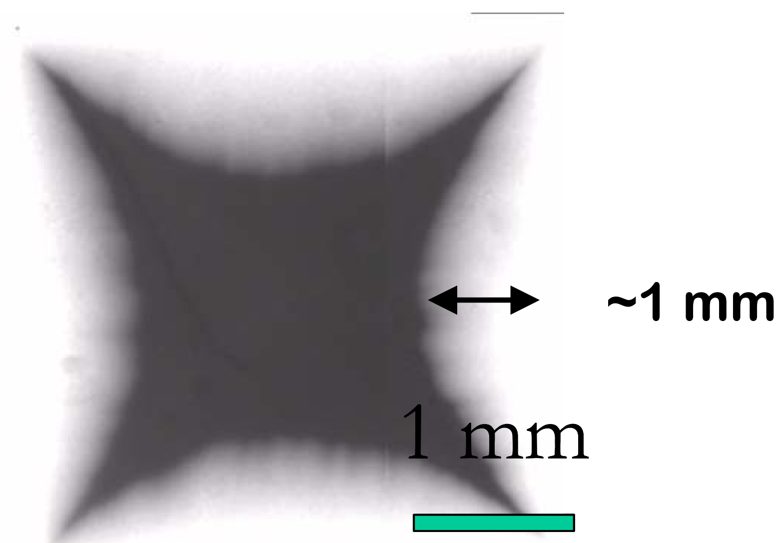
Profilometry combined with FE modeling ongoing at Saclay;

Other ideas?

Magneto-Optics?

Magneto-Optics gives us an idea of how far fields are penetrating in the DC case:





Tri-crystal sample, T=5.5 K, μ_0H=120 mT, FE~3

Physics of the Quench Process

Physics of Quenched Zone:

Knobloch's finite element thermal model:

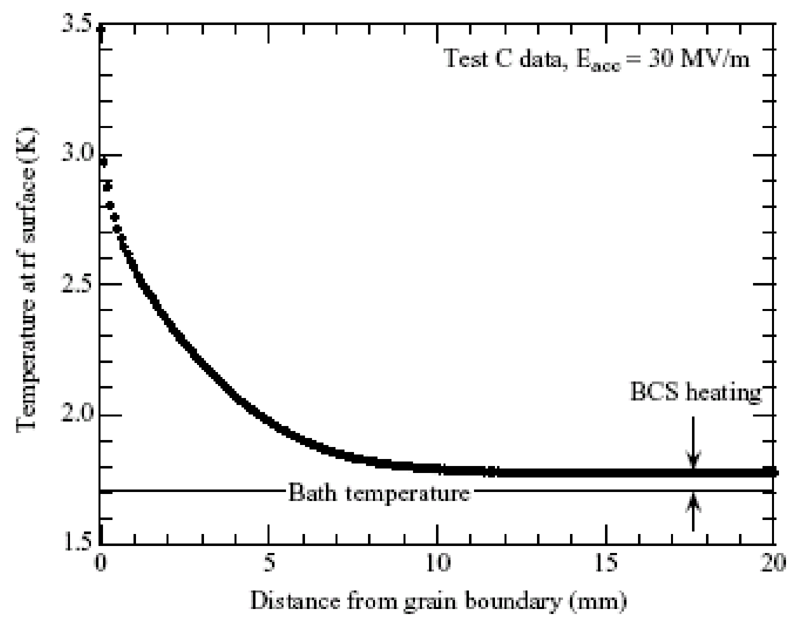
3 K peak temperature

10 mm "size"

order mJ enthalpy

Quench energy problem?

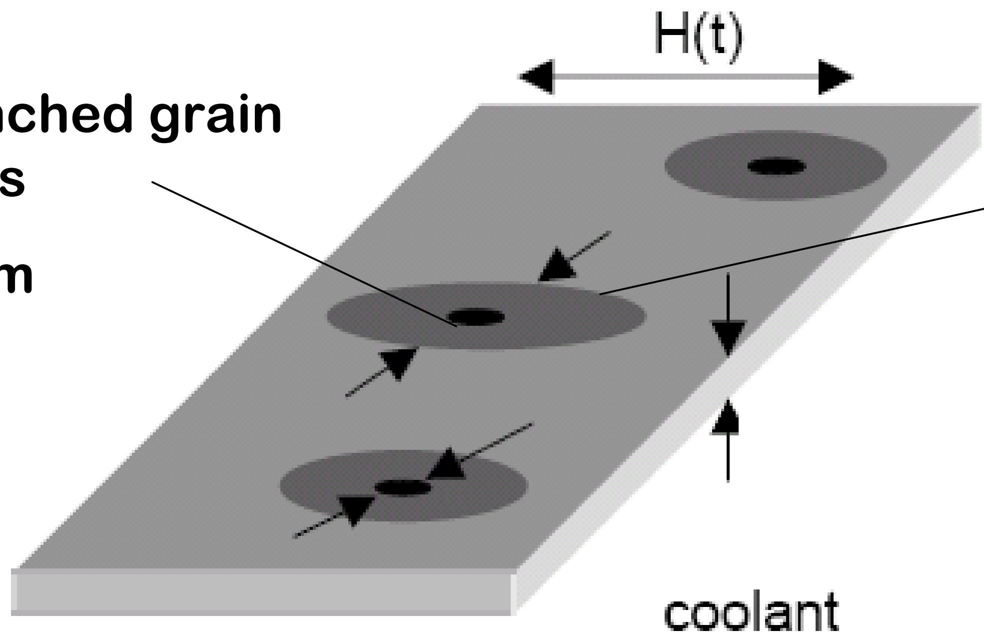
(a)



Gurevich's Hot Spot Model

Quenched grain edges

~ 1 μm



thermally affected zone: ~ 5 mm and growing with B!

$$L(B) \cong \frac{L_h}{\sqrt{1-\left(B/B_{rf,crit}\right)^2}}$$

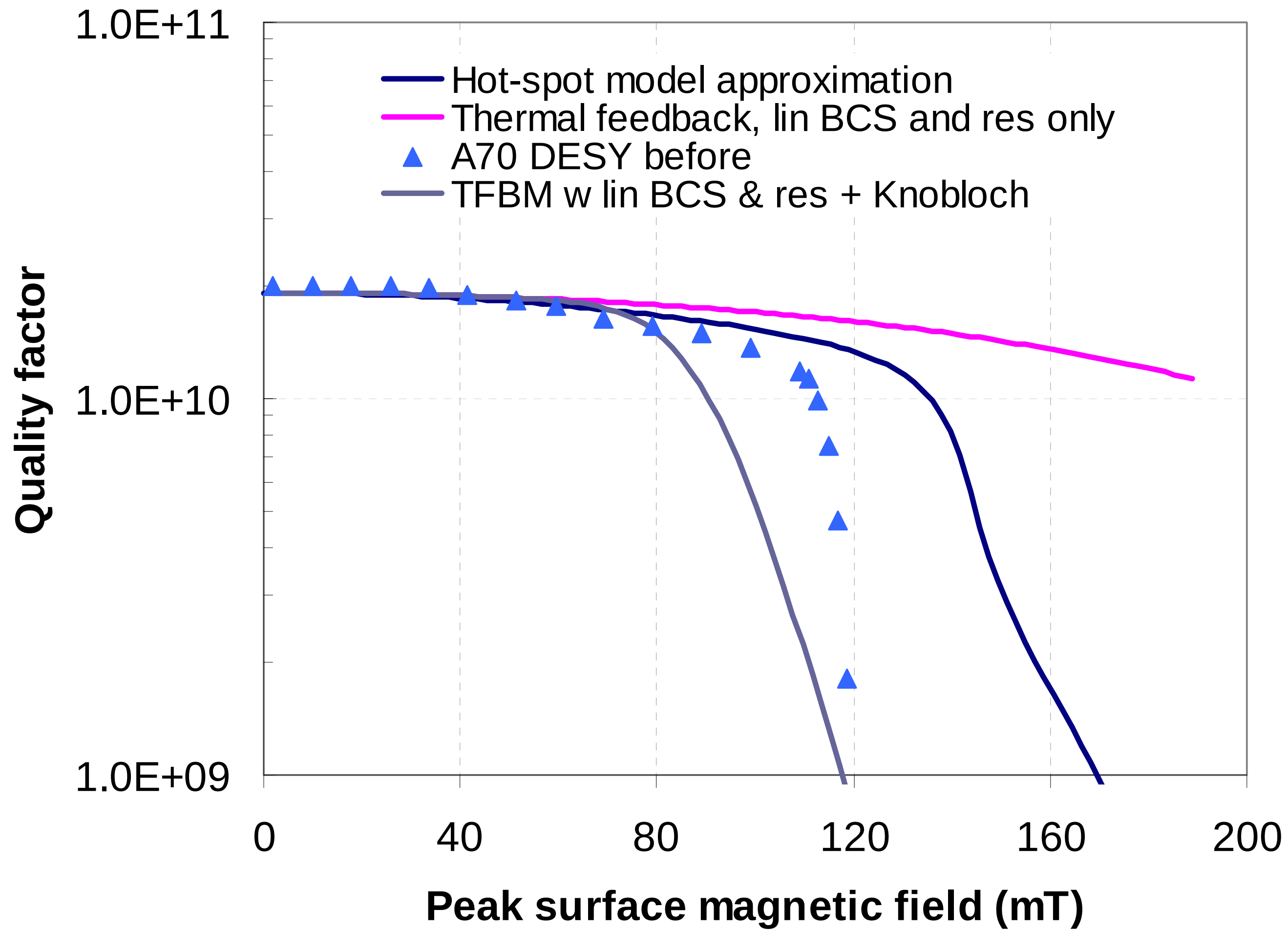
$$L_h = d\sqrt{1+\frac{\kappa}{d\alpha}}$$

Growth of the thermally affected zone introduces additional dependence of surface resistance on B!

Quenched Edges as Hot Spots

Result obtained:

Effect is much weaker than predicted with Knobloch model!



obtained from a TFBM calculation with linear BCS and residual only

$$Q(B) \cong \frac{Q(0) e^{-\frac{(T_m - T_0)}{T_0}\frac{\Delta}{k_B T_0}}}{1 + f_{HS}(B)}$$

Conclusions

•Jens Knobloch presented a well thought out model to predict the effect of field enhancement on grain edges on surface resistance. There is consensus that this model is discussing a relevant issue;

•Several issues indicate that the Knobloch model needs to be improved. Among them is the “baking effect” and the quenching of a Saclay cavity as a result of a grain.

•A first step toward improving the model is to integrate it into Gurevich’s “hot spot” model. This was accomplished here. The hotspot model would predict a weaker effect?

•Next steps: 1) Get more realistic surface profiles! 2) Understand quenching process (thermal models,..etc)! .....

•Everybody is invited to participate!

Knobloch Model Step by step (4/17)

Cavity effective area:

$$A_{eff} = \frac{\oint_{A_{cavity}} H^2(x)\, d^2x}{H_{peak}^2} = \frac{2\omega U}{G H_{peak}^2} \qquad \left(m^2\right)$$

1-cell TESLA cavity:

$$A_{eff} = \left| \omega U = \frac{(EL)_{acc}^2}{2 R/Q} \right| = \frac{\left(\lambda_{RF}/2\right)^2}{\left(\frac{\frac{4mT}{MV/m}}{\mu_0}\right)^2 G\left(\frac{R}{Q}\right)} \rightarrow A_{eff} \approx 0.06 m^2$$

R/Q=96.15Ω

G=225Ω

Simple estimate: $A_{eff} \approx \pi \lambda_{RF} w, \quad w \approx 8.4cm \rightarrow A_{eff} \approx 0.61 m^2$

Knobloch Model Step by step (6 / 17)

Total # of grains:

$$N_g \approx \frac{A_{eff}}{l_g^2},\ l_g \approx 0.1mm \rightarrow N_g \approx 6.1\times 10^6$$

average grain size takes into account weld region

Total # of grain edges:

4 edges / grain

$$N_{ge} \approx \frac{4}{2} N_g,\quad l_g \approx 0.1mm \ \rightarrow \ N_{ge} \approx 1.2\times 10^7$$

only the “higher” edge of two neighboring grains counts

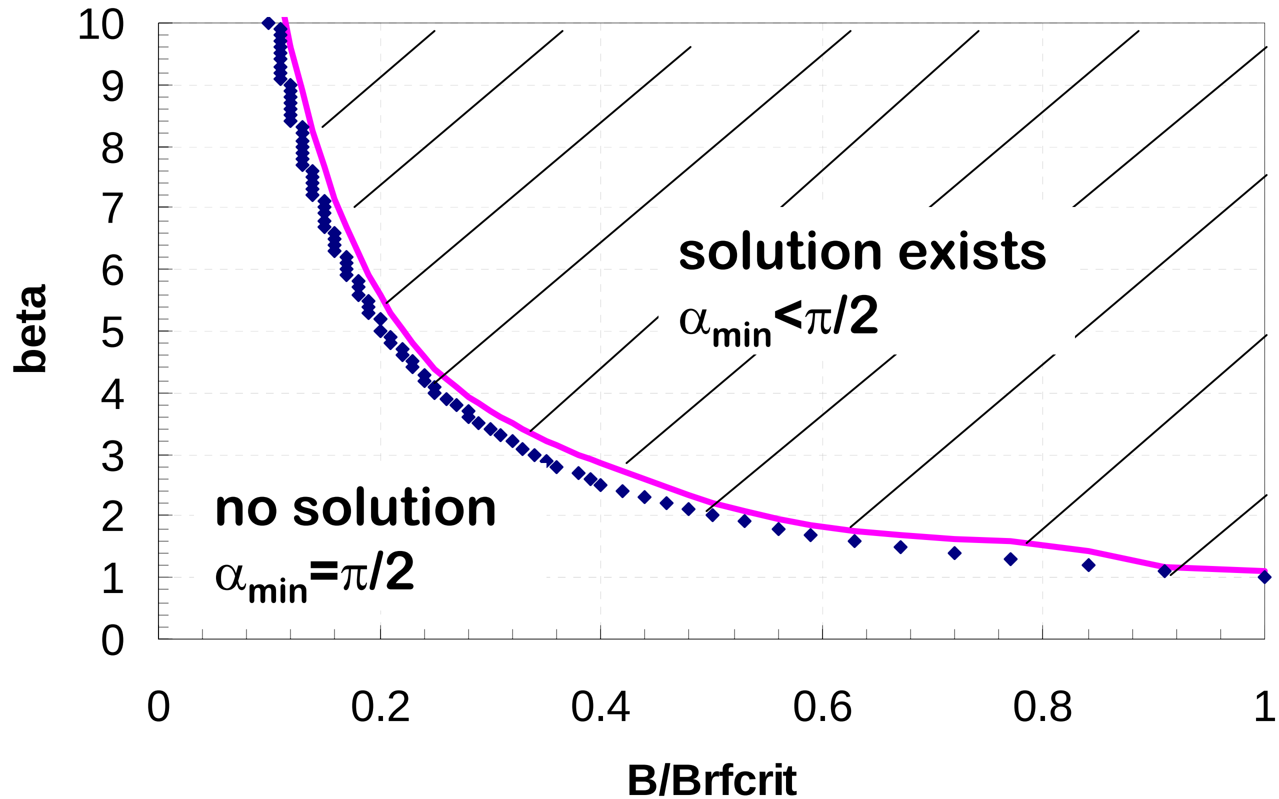
Knobloch Model Step by step (10/17)

Integration over α:

$$\beta_{eff} B = B\sqrt{\left(\beta \sin(\alpha)\right)^2 + \cos^2(\alpha)} = B_{rf,crit}$$

Integration boundaries:
(α_{min},π/2);

The equation for β -effective can be solved only for certain combinations of field, B, and FE β – see contour:

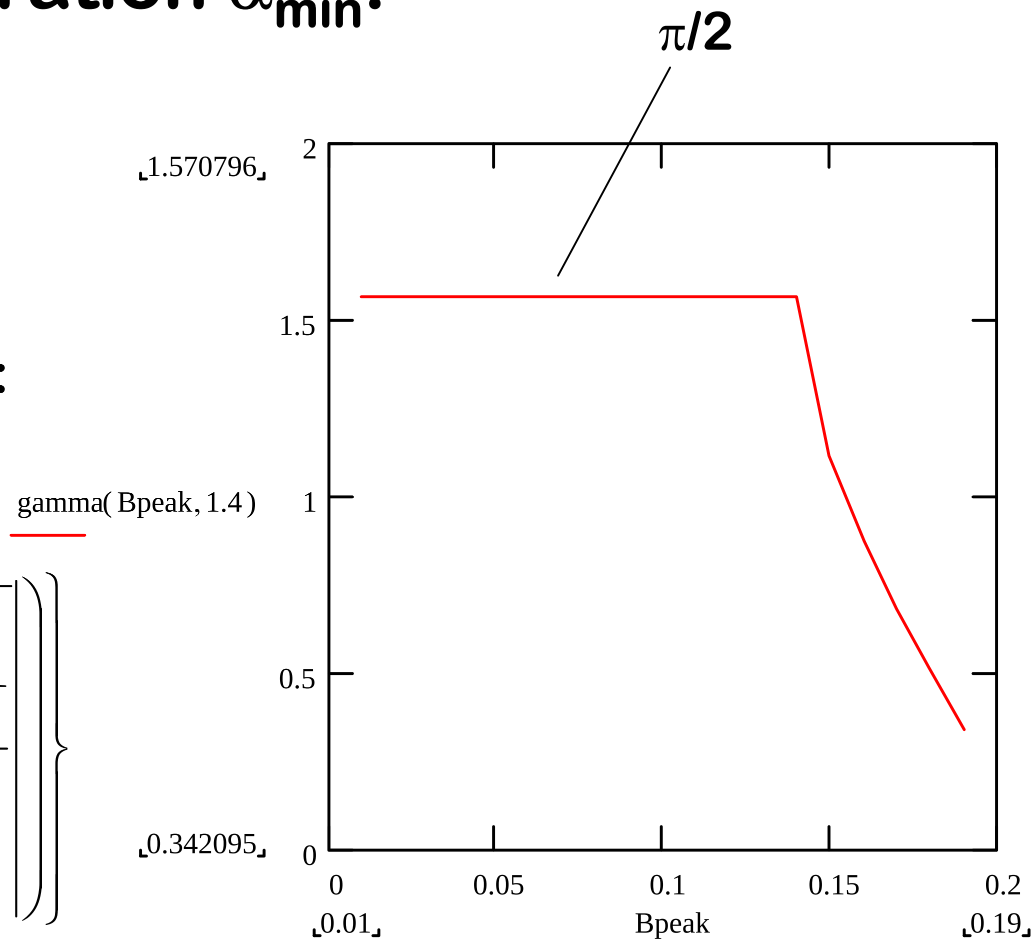


Knobloch Model Step by step (11/17)

Lower angle of integration α_{min}:

α_{min} is the angle at which, for a given field B and a given FE β, a particular grain edge reaches $B_{rf,crit}$ (I.e. quenches):

$$\alpha_{min}(B,\beta) = \mathbf{Re}\left\{ \mathbf{arcsin}\left(\left| \sqrt{\frac{\left(\frac{B_{rfcrit}}{B}\right)^2 - 1}{\beta^2 - 1}} \right| \right) \right\}$$



Knobloch Model Step by step (15/17)

Total resistance can be calculated from the total number of quenched grain-edges, N_{geq}, the grain size, l_g, the "width" of the quenched grain edge, w_{nc}, and the normal state RF resistance, $R_{s,norm}$, of Nb at low temp:

$$\frac{1}{2} R_s H^2 A_{eff} = \frac{1}{2} R_{s,norm} \beta_0^2 B_{peak}^2 l_g w_{nc} N_{geq} \qquad (W)$$

$$\Rightarrow \; R_{s,geq} = \frac{1}{A_{eff}} R_{s,norm} \beta_0^2 l_g w_{nc} N_{geq} \qquad (\Omega)$$

$R_{s,norm}$~1.5 mΩ

$$R_{s,geq}(B) = \frac{1}{A_{eff}} R_{s,norm} \beta_0^2 l_g w_{nc} \frac{2}{\pi} N_g \int_{\beta_{\min}(B)}^{\beta_{\max}} \int_{\alpha_{\min}(B,\beta)}^{\pi/2} n(\beta) \left(\frac{\beta_{eff}(\alpha,\beta) B}{B_{rf,crit}} \right)^{2.03} d\beta d\alpha$$

Quenched Edges as Hot Spots

Integration of Knobloch and Gurevich models:

$$\eta = \frac{\frac{1}{2} R_{s,norm} \beta_0^2 B^2 l_g w_{nc}}{\frac{1}{2} R_s(B,T,..) B^2 A_{eff}}$$

enhancement of power dissipation in hot spot over “regular” spot

$$f_{HS}(B) \cong \left(\frac{\langle \eta \rangle \times n_{geq}(B) \times \pi L_h^2}{1 - \left(\frac{B}{B_{rf,crit}} \right)^2} \right)$$

growth of hot spots with field due to thermal diffusion; Increase of resistance follows
Note: # of hot spots also increases with field!

$$R_s^{total}(B,T,..) \cong (1 + f_{HS}(B)) R_s^{uniform}(B,T,..)$$

increase of total resistance before thermal feedback!

Input this correction into “uniform” surface thermal feedback model;